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RESPONSE OF FGM PLATE UNDER CENTRAL POINT LOAD SUBJECTED TO BOUNDARY CONDITIONS

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ABSTRACT

Functionally Graded Material (FGM) is a case of composites wherein material properties are varied gradually by following certain material distribution laws. The volume fraction is controlled by Power law distribution and Sigmoid law distribution. Various structure forms made of FGMs are available such as shells, plates, beams etc. Plate deformation theories (such as First order and Third order deformation theories) are used to calculate response of FGM plate. First order theory is used for thin plates. Finite Element Analysis (FEA) has been popularly in use for researchers. In the present work, shear deformation theory of First order has been used for the analytical response evaluation of FGM plates. Central point load is applied on a plate made of FGM. Also, the plate is applied with a certain boundary conditions. Parametric results for Power law-FGM and Sigmoid law-FGM plate are evaluated and presented in terms of predefined non-dimensional parameters.

KEYWORDS:FEM, FGM, FSDT, Deflection & Stress

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Original Article

1. INTRODUCTION

The heterogeneous composite materials contain two or more material compositions. Functionally Graded Material (FGM) is developed with advancements in heterogeneous composites. Material properties are varied gradually in one or more than one directions. The properties are dependent distribution of the material volume fraction. The volume fraction is controlled by certain laws among which Power law distribution (P-FGM) and Sigmoid laws distribution (S-FGM) are two of the most used laws. Various deformation theories for plate have used by research to compute the performance of the graded plates. Reddy [1] used Classical plate theory (CPT) and Third Order Shear Deformation Theory (TSDT). FSDT and TSDT are found reliable with their own constraints for the FGM plates. FSDT is appropriate for thin plates since the effect of shear stress of transverse direction is relatively small. While TSDT has been used byMa and Weng[2]. Finite volume theory have been developed by Marcio et.al. [3] for parametric formulation of the FGM structure. Armin [4] conducted FE analysis for design and analysis of FG materials beam with a particular application of Piezoelectric materials. Nguyen et. al. [5] presented modified FE approach where triangular plate elements are obtained by strain smoothing (node based). The formulation used approximation in linear form which made its application into FE program simpler and efficient. Zakia et.al. [6] conducted analysis to mitigate interface delamination of FG sandwich Plates. Bhandari and Purohit [7] used the combination of Aluminum (metal) and Zirconia (Ceramic) as FGM for the performance evaluation of FGM plate under certain boundary conditions. Sharma et.al. [8] used principle of virtual displacement and Generalized plate theory (GPT) which includes CPT to investigate thermo mechanical buckling response of simply-supported FGM plate. Sharma [9] explored Ni/Al_2O_3 FG plate,

used FSDT, applied mechanical load and observed response for stability and failure using non-linear FE formulation. Xiaohui [10] included normal strain in transverse direction and developed sinusoidal model for mechanical response of FGM plate with various configurations. Moita et. al. [11] developed FE model with a triangular flat plate to present buckling response of FG plate under thermo mechanical conditions.

In present work, Aluminum-Zirconia (Al-ZrO_2) FG plate is subjected to central point load. Further various boundary conditions are applied and response is recorded. The FSDT is the plate theory used for thin plate. Combination of clamped (C), Free (F) and simply supported (S) boundary condition are applied to the plate. The FE method and the ANSYS software are used for modelling and analysis. The material distribution is varied using Exponential law, Power law and Sigmoid law. The results depicted non-dimensional parameters which are predefined.

2. METHODOLOGY AND PROBLEM FORMULATION

2.1 Constituent Materials

The FG plate modelled in the present work is made up of zirconia (ZrO_2) as ceramic and Aluminum (Al) as metal. Inputs for the problem are: modulus of elasticity, Poisson's ratio, density etc. of the constituent materials i.e. Aluminum and Zirconia.

2.2 Gradation

FG plate is graded along one dimension only i.e. thickness direction and hence properties are obtained along the thickness direction using the properties distribution laws which are Exponential law, Power law and Sigmoid law. The material properties are obtained for the following volume fraction index 'n' values: 0.1, 0.2, 0.5, 1, 2, 5, 10, 100, n=infinity (metal) and n=0 (Ceramic).

2.3 Loading and Dimensions

Plate of size 1mx1m is considered here i.e. aspect ratio is taken unity. The load applied is concentrated, applied at the centre and the value of the load is 10E6N.

2.4 Boundary Conditions

Combinations of clamped (C), Free (F) and simply supported (S) boundary condition are applied to the plate.

2.5 Numerical Method

Modelling is done using finite element method and the computation is done with the help of computer software. Deflection (uz), tensile stress (σ_x), shear stress (σ_{xy}), strain (e_x) and shear strain (e_{xy}) are computed. The parameters are non-dimensionalized as follows:

non-dimensional deflection $\overline{u_z}$ = uz / h,

non-dimensional tensile stress $(\overline{\sigma_x})$ = σ_x / p and

non-dimensional shear stress $(\overline{\sigma_{xy}})$ = σ_{xy} / p.

where 'h' is 0.02m (plate thickness) and 'p' is (1E6).

2.6 Finite Element Modelling:

First order shear deformation theory (FSDT) is used which is suitable for thin plates.

First-order plate theory is based on the displacement field which can be expressed in the form equation (5)

$u(x,y,z)=u_o(x,y)+z\Phi_x(x,y)$

$v(x,y,z)=v_o(x,y)+z\Phi_y(x,y)$

$w(x,y,z)=w_o(x,y)$ (5)

where (u_o,v_o, w_o, Φ_x, Φ_y) are to be determined.

The minimum potential energy (PE) principle is used to model plate equilibrium. The total P.E is in the form equation (6).

$$\Pi=(0.5\int_A\{\varepsilon_b^0\}^T[DE_b]\{\varepsilon_b^0\}dA)+(0.5\int_A\{\varepsilon_s^0\}^T[DE_s]\{\varepsilon_s^0\}dA)-\Sigma\{P\}\{u^o\} \quad (6)$$

where

Integration of the plate constituent material properties (through the thickness of the plate) is performed to obtain equivalent layer of the FG plate as in equations (7a and 7b)

$$[DE_b] = \int_{-h/2}^{h/2}\{ Z_b \}^T [D_b]^T \{Z_b\}\, dz \quad (7a)$$

$$[DE_s] = \int_{-h/2}^{h/2}\{ Z_s \}^T [D_s]^T \{Z_s\}\, dz \quad (7b)$$

where $[D_b]$ and $[D_s]$ are matrices in the bending and shear for the material matrices, respectively.

3. RESULTS

3.1 Effect of Boundary Conditions on FGM Plate under Point Load

The graded plate is applied with a central concentrated point load and various boundary conditions. The computed results (which include deflection (uz), tensile stress (σ_x), shear stress (σ_{xy}), strain (e_x) and shear strain (e_{xy})) are non-dimensionalized. The plate is square and the volume fraction is varied as per E-FGM (Exponential), P-FGM (Power) and S-FGM (Sigmoid). The 'n' is varied and results are obtained for various 'n': 0.1, 0.2, 0.5, 1, 2, 5, 10, 100, n:$\propto$ (metal) and n:0 (Ceramic).

3.1.1 Non-Dimensional Deflection ($\overline{u_z}$)

Table 1 and 2 show the values of non-dimensional deflection and Figure 1 and Figure 2 show the comparative charts for variation of end conditions.

It can be stated that:

- The non-dimensional deflection is maximum under FFSS end condition and minimum for all end conditions clamped or fixed (CCCC).
- It is also clearly observed that incremental change in 'n' causes increment in deflection.
-

Table 1: Effect of End Conditions on Non-Dimensional Deflection ($\overline{uz}$) for P (Power) -FGM

P-FGM						Exp.-FGM
END CONDITIONS	**n:0**	**0.5**	**1**	**5**	**100**	
SSSS	5.4	6.9	7.7	9.0	10.6	8.0
CCCC	1.7	2.1	2.4	2.8	3.3	2.0
CSCS	2.5	3.2	3.6	4.2	5.0	4.0
FCFC	3.8	4.9	5.4	6.4	7.5	6.0
FFCC	57	73	81	96	112	84.0
SSCC	54	70	78	92	108	81.0
FFSS	236	304	338	398	467	349
CSSS	3.8	4.8	5.4	6.3	7.4	6.0
FSSS	16.9	21.7	24.1	28.5	33.4	25.0
CFSS	7.9	10.1	11.3	13.3	15.6	12.0

Table 2: Effect of End Conditions on Non-Dimensional Deflection ($\overline{uz}$) for Sigmoid-FGM

S-FGM						
END CONDITIONS	**n:0**	**0.5**	**1**	**5**	**100**	**∝**
SSSS	5.4	7.5	7.7	8.0	8.1	11.5
CCCC	1.7	2.3	2.4	2.5	2.5	3.6
CSCS	2.5	3.5	3.6	3.8	3.8	5.4
FCFC	3.8	5.3	5.4	5.7	5.8	8.2
FFCC	57	79	81	85	86	122
SSCC	54	76	78	82	82	117
FFSS	236	331	338	355	358	510
CSSS	3.8	5.2	5.4	5.6	5.7	8.1
FSSS	16.9	23.6	24.1	25.4	25.6	36.4
CFSS	7.9	11.0	11.3	11.9	12.0	17.0

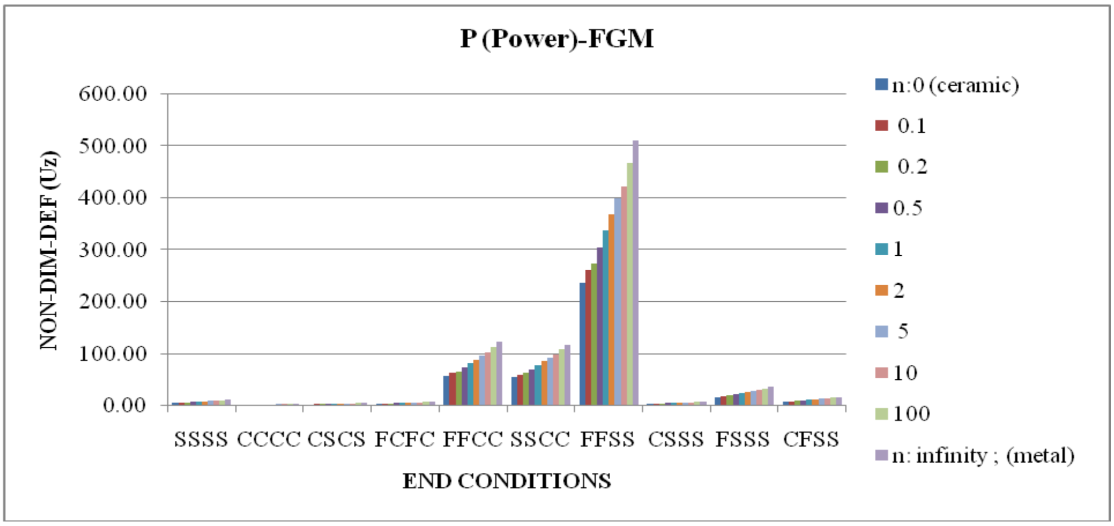

Figure 1: Effect of End Conditions and ‘n’ on Non-Dimensional Deflection ($\overline{u_z}$) for P (Power)-FGM.

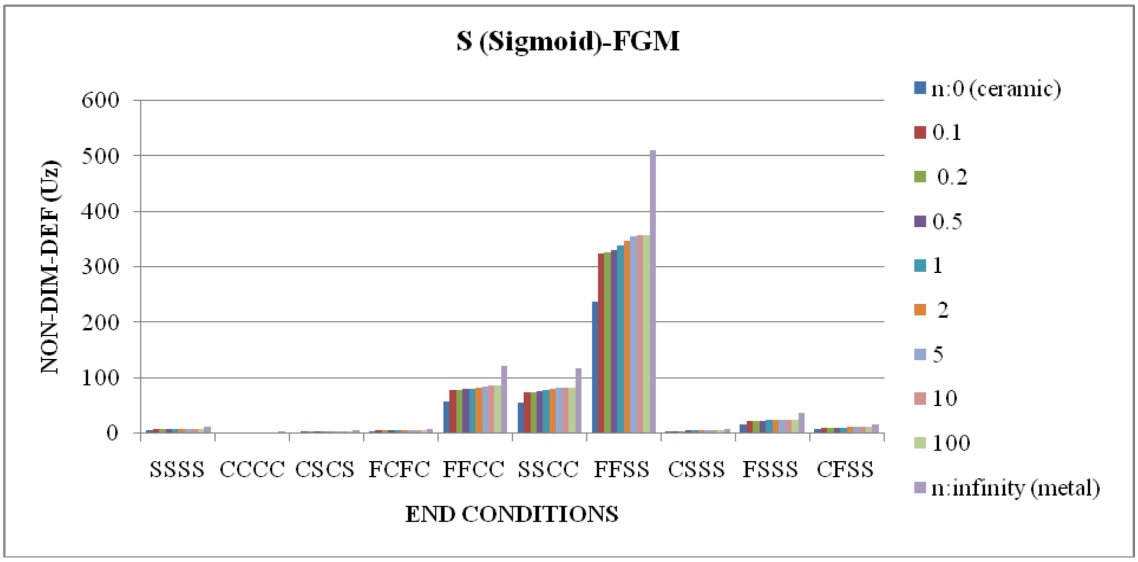

Figure 2: Effect of End Conditions and 'n'on non-Dimensional Deflection ($\overline{u_z}$) for S (Sigmoid)-FGM.

Figure 3 shows variation of deflection for various types of plate which are n:0 (Ceramic), n:∝ (Metal), P(Power)-FGM (n:0.5& 2), S(Sigmoid)-FGM (n:0.5 & 2) and E (Exponential)-FGM. It is clear that the non-dimensional deflection under the FFSS end condition in case of n2 (P) is ($\overline{u_z}$ = 369) and that of n2 (S) is ($\overline{u_z}$ =347). Non-dimensional deflection for E-FGM ($\overline{u_z}$ = 349) is more than that of n2 (S) and less than that of n2 (P).

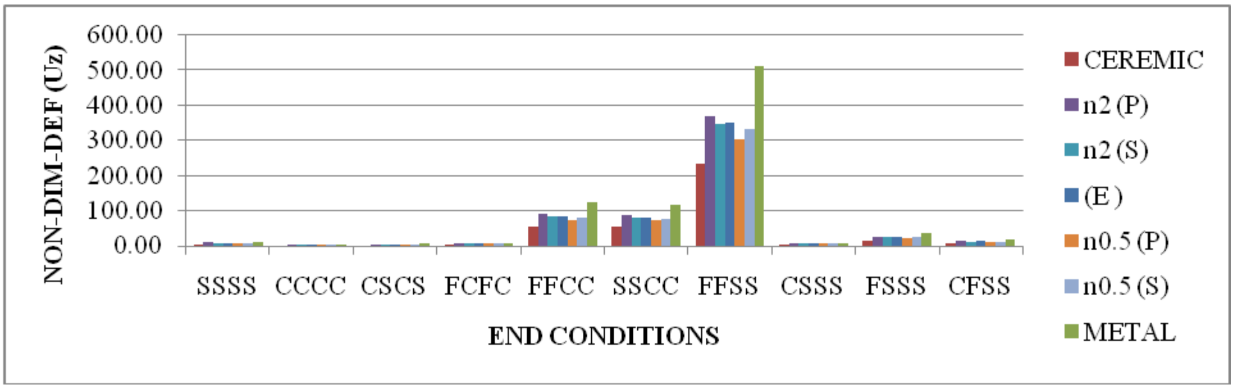

Figure 3: Effect of end Conditions and 'n' on non-Dimensional Deflection ($\overline{u_z}$) for FGM's, Metal and Ceramic

3.1.2 Non-Dimensional Tensile Stress ($\overline{\sigma_x}$)

Table 3 and 4 show computed values of non-dimensional tensile stress ($\overline{\sigma_x}$) and Figure4 and Figure5 show the comparative charts for various end conditions.

It is stated that

- Non-dimensional tensile stress grows as 'n' increases.
- The end condition (FFCC) gives maximum tensile stress (37777) while boundary condition (SSCC) gives second highest value of tensile stress (34716). The boundary condition (CSCS) gives minimum value (3459).

Table 3: Effect of End Conditions on Non-Dimensional Tensile Stress ($\overline{\sigma_x}$ $x1000$) for P (Power)-FGM

	P-FGM					Exp.-FGM
END CONDITIONS	**n:0**	**0.5**	**1**	**5**	**100**	
SSSS	6.92	8.04	8.56	9.56	9.92	8.72
CCCC	4.39	5.10	5.43	6.07	6.30	5.54
CSCS	3.49	4.06	4.32	4.82	5.01	4.40
FCFC	7.82	9.09	9.68	10.8	11.2	9.87
FFCC	25.7	29.8	31.7	35.5	36.8	32.4
SSCC	23.6	27.4	29.2	32.6	33.8	29.7
FFSS	16.7	19.4	20.7	23.1	24.0	21.1
CSSS	5.06	5.88	6.26	6.95	7.22	6.84
FSSS	15.7	18.2	19.6	22.3	22.3	20.2
CFSS	11.5	13.9	14.0	16.4	17.6	15.0

Table 4: Effect of End Conditions on Non-Dimensional Tensile Stress ($\overline{\sigma_x}x1000$) for S (Sigmoid)-FGM

	S-FGM					
END CONDITIONS	**n:0**	**0.5**	**1**	**5**	**100**	**∝**
SSSS	6.24	8.24	8.62	8.44	9.35	10.2
CCCC	4.95	5.47	5.35	5.14	5.99	6.57
CSCS	3.95	4.53	4.22	4.64	4.11	5.35
FCFC	7.29	9.25	9.81	10.0	10.9	11.1
FFCC	25.6	31.7	31.8	32.5	33.7	37.8
SSCC	23.2	28.1	29.1	30.3	31.7	34.6
FFSS	16.8	20.0	20.4	21.7	22.2	24.3
CSSS	5.64	6.61	6.62	6.68	6.81	7.39
FSSS	15.7	19.0	19.6	20.5	21.6	23.3
CFSS	11.5	14.2	14.0	15.8	15.2	17.7

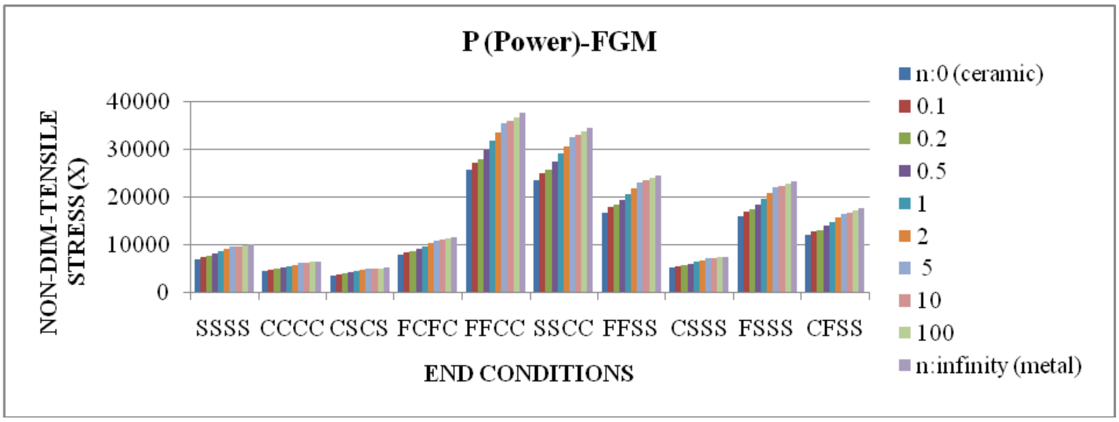

Figure 4: Effect of End Conditions on Non-Dimensional Tensile Stress ($\overline{\sigma_x}$) for P (Power)-FGM.

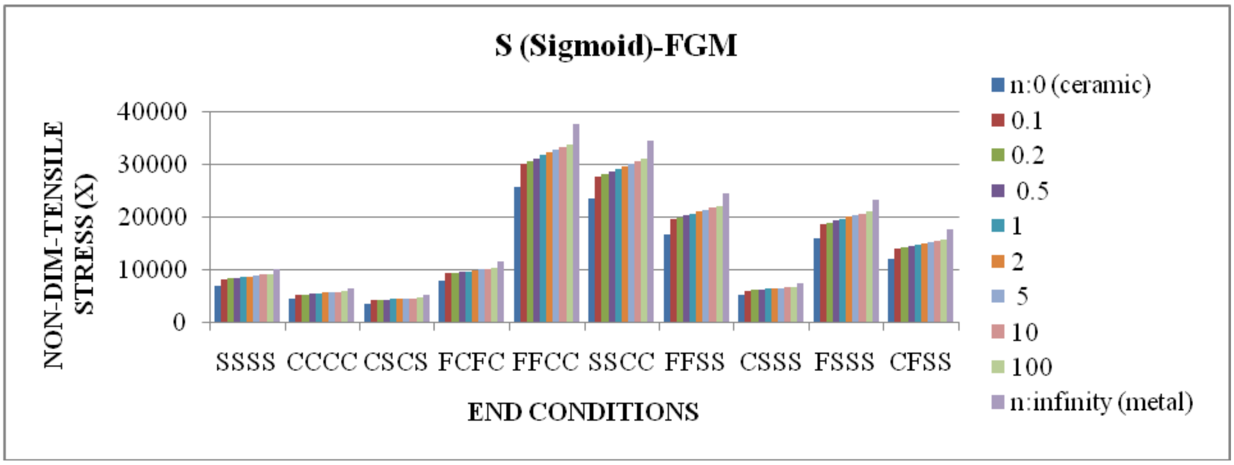

Figure 5: Effect of End Conditions on Non-Dimensional Tensile Stress ($\overline{\sigma_x}$) for S (Sigmoid)-FGM.

Figure 6 shows variation of tensile stress for various types of plate which are n:0 (Ceramic), n:∝ (Metal), P(Power)-FGM (n:0.5 & 2), S(Sigmoid)-FGM (n:0.5 & 2) and E (Exponential)-FGM. It is clear that the non-dimensional tensile stress under the FFSS end condition in case of n2 (P) ($\overline{\sigma_x}$ = 21842) and that of n2 (S) is ($\overline{\sigma_x}$=21100). Non-dimensional tensile stress for E-FGM ($\overline{\sigma_x}$ = 21139) is more than that of n2 (S) and less than that of n2 (P).

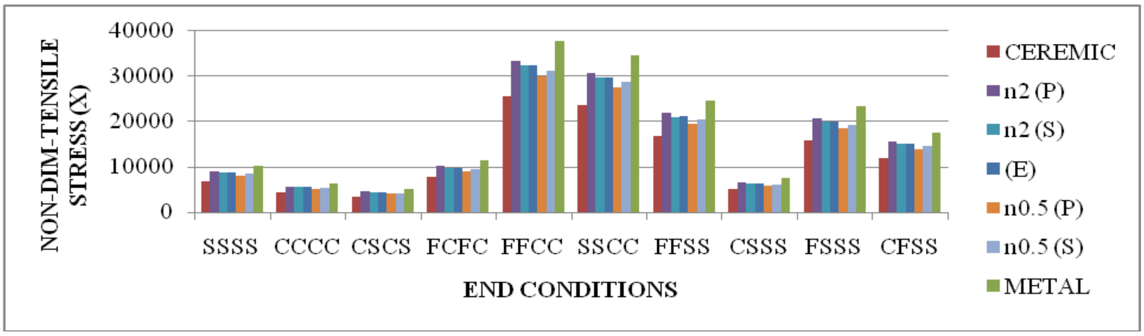

Figure 6: Effect of End Conditions on Non-Dimensional Tensile Stress ($\overline{\sigma_x}$) for FGM's, Metal and Ceramic

3.1.3 Non-dimensional Shear Stress ($\overline{\sigma_{xy}}$)

Table 5 and 6 show the computed values of non-dimensional shear stress ($\overline{\sigma_{xy}}$) and Figure7 and Figure 8 show the comparative charts for various end conditions.

It is stated that

- Non-dimensional shear stress grows as 'n' increases.
- The boundary condition (SSFF) gives maximum shear stress (4922) while boundary condition (CCCC) gives minimum value (245).

Table 5: Effect of End Conditions on Shear Stress ($\overline{\sigma_{xy}}$) for P (Power)-FGM

	P-FGM					Exp.-FGM
END CONDITIONS	**n=0**	**0.5**	**1**	**5**	**100**	
SSSS	921	1068	1133	1258	1308	1154
CCCC	245	284	302	335	348	307

CSCS	412	478	507	563	585	516
FCFC	311	360	382	424	441	389
FFCC	1050	1218	1292	1434	1492	1316
SSCC	1061	1230	1305	1448	1507	1329
FFSS	3402	3944	4186	4645	4832	4263
CSSS	754	874	928	1030	1071	945
FSSS	1307	1516	1609	1785	1857	1638
CFSS	595	690	732	812	845	745

Table 6: Effect of Boundary Conditions on Shear STRESS ($\overline{\sigma_{xy}}$) for S (Sigmoid)

S-FGM						
END CONDITIONS	**n=0**	**0.5**	**1**	**5**	**100**	**∝**
SSSS	921	1116	1133	1145	1157	1333
CCCC	245	297	302	305	308	355
CSCS	412	500	507	512	518	596
FCFC	311	377	382	386	390	450
FFCC	1050	1273	1292	1306	1320	1520
SSCC	1061	1286	1305	1319	1333	1535
FFSS	3402	4124	4186	4230	4275	4923
CSSS	754	914	928	938	948	1091
FSSS	1307	1585	1609	1626	1643	1892
CFSS	595	721	732	740	748	861

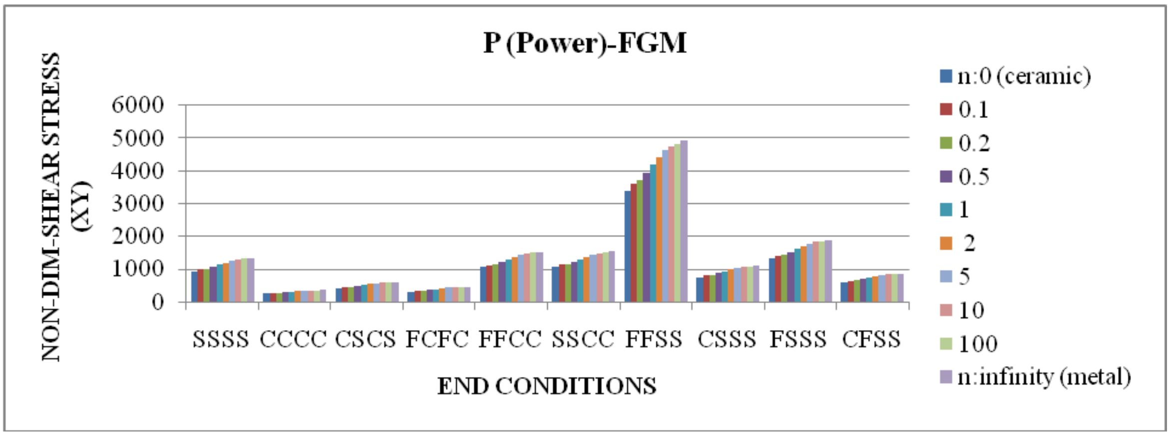

Figure 7: Effect of End Conditions on Non-Dimensional Shear Stress ($\overline{\sigma_{xy}}$) for P (Power)-FGM.

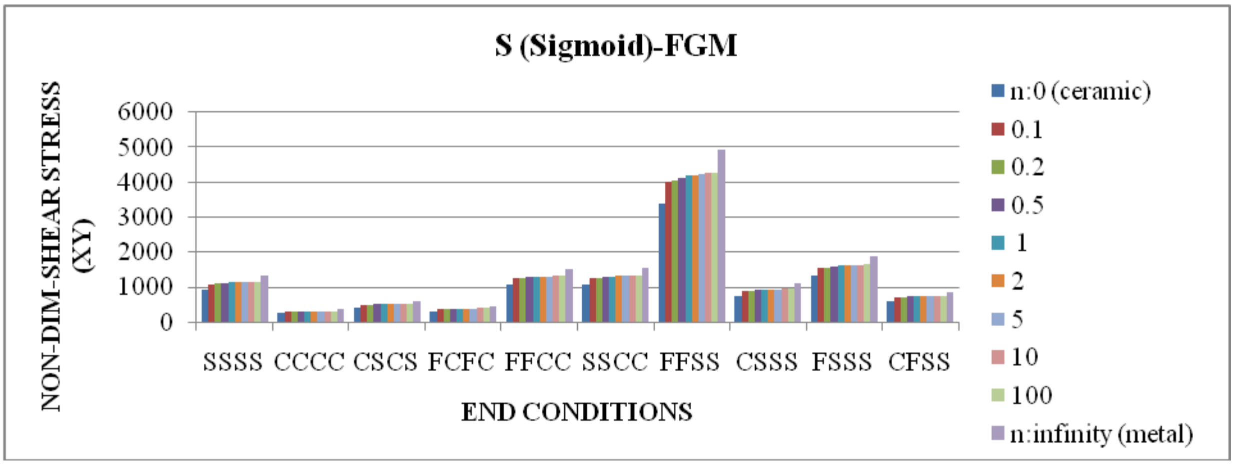

Figure 8: Effect of End Conditions on Non-Dimensional Shear Stress ($\overline{\sigma_{xy}}$) for S (Sigmoid)-FGM.

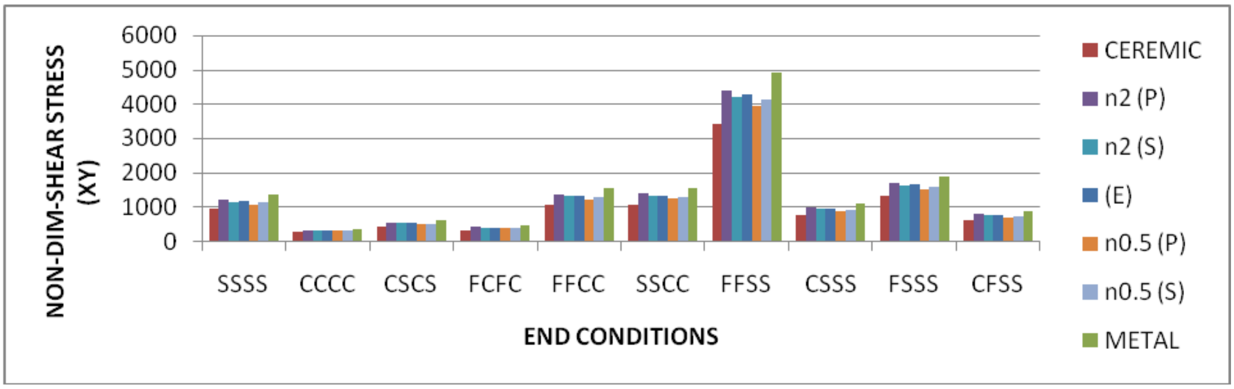

Figure 9: Effect of End Conditions on Non-Dimensional Shear Stress ($\overline{\sigma_{xy}}$)for FGM's, Metal and Ceramic.

Figure 9 shows variation of shear stress for various types of plate which are n:0 (Ceramic), n:∝ (Metal), P(Power)-FGM (n:0.5 & 2), S(Sigmoid)-FGM (n:0.5 & 2) and E (Exponential)-FGM. It is clear that the nondimensional shear stress under the FFSS end condition in case of n2 (P) ($\overline{\sigma_{xy}}$ = 4405) and that of n2 (S) is ($\overline{\sigma_{xy}}$ =4210). Non-dimensional shear stress for E-FGM ($\overline{\sigma_{xy}}$ = 4262)) is more than that of n2 (S) and less than that of n2 (P).

3.1.4 Strain (ex)

Table 7 and 8 show the values of strain (e_x) and Figure10 and Figure11 show the comparative charts for various end conditions.

It is stated that

- The pure ceramic plate has the minimum strain (e_x) and the pure metal plate has the maximum Strain (e_x).
- The Strain (e_x) grows with increment of 'n' in case of P (Power)-FGM and S (Sigmoid)-FGM. For pure metal, sudden rise strain is observed.
- The clamped - free (CCFF) boundary conditions gives maximum Strain (e_x) and all edges fixed of clamped (CCCC) boundary condition gives minimum strain (e_x).

Table 7: Effect of End Conditions on Strain (e_xx1000) for P (Power)-FGM

	P-FGM						Exp.-FGM
END CONDITIONS	**n=0**	**0.5**	**1**	**2**	**5**	**100**	
SSSS	32	38	40	43	48	61	41
CCCC	5	6	7	7	8	10	7
CSCS	14	16	18	19	21	27	18
FCFC	97	114	122	131	145	186	125
FFCC	319	374	401	430	476	610	412
SSCC	293	344	369	395	437	561	379
FFSS	111	130	139	149	165	212	143
CSSS	22	25	27	29	32	42	28
FSSS	105	124	133	142	157	202	136
CFSS	149	174	187	200	222	284	192

Table 8: Effect of Boundary Conditions on Strain (e_x x1000) for S (Sigmoid)-FGM

	S-FGM						
END CONDITIONS	**n=0**	**0.5**	**1**	**2**	**5**	**100**	**∝**
SSSS	32	40	40	41	41	42	69
CCCC	5	7	7	7	7	7	12
CSCS	14	17	18	18	18	18	30
FCFC	97	121	122	123	124	128	209
FFCC	319	397	401	404	408	421	689
SSCC	293	365	369	371	375	387	633
FFSS	111	138	139	140	142	146	239
CSSS	22	27	27	27	28	29	47
FSSS	105	131	133	133	135	139	227
CFSS	149	185	187	188	190	196	321

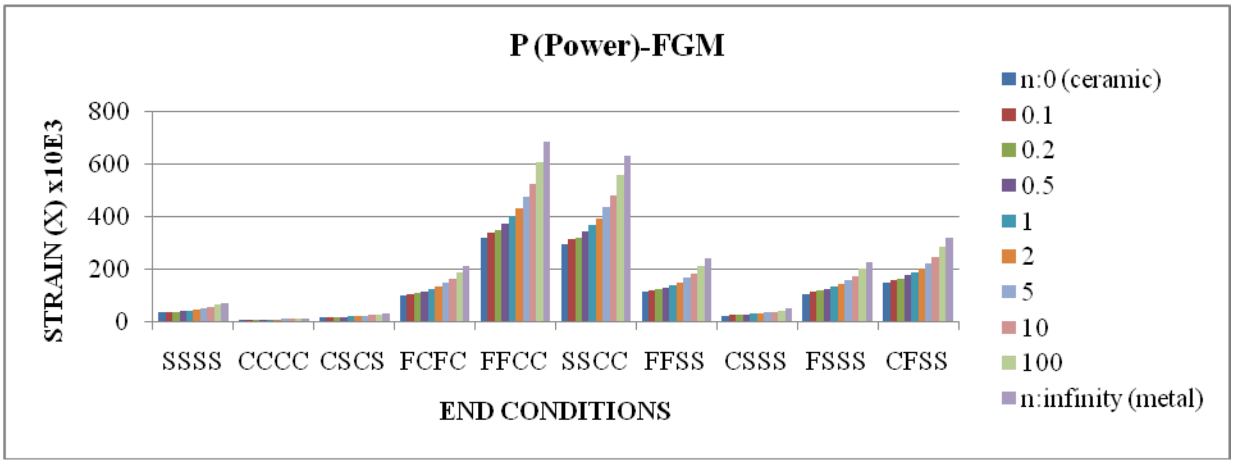

Figure 10: Effect of End Conditions on Strain (e_x) for P (Power)-FGM.

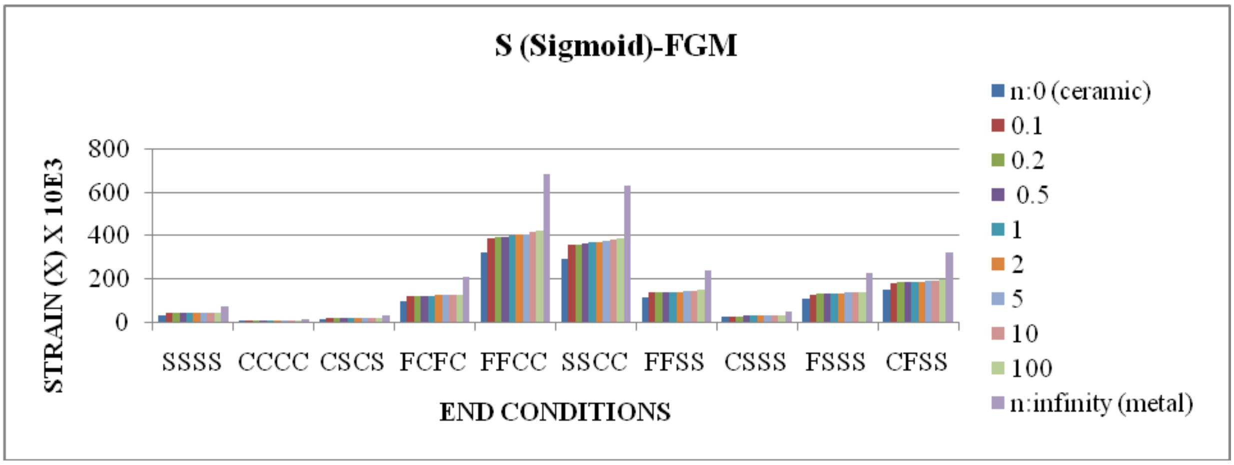

Figure 11: Effect of End Conditions on Strain (e_x) for S (Sigmoid)-FGM.

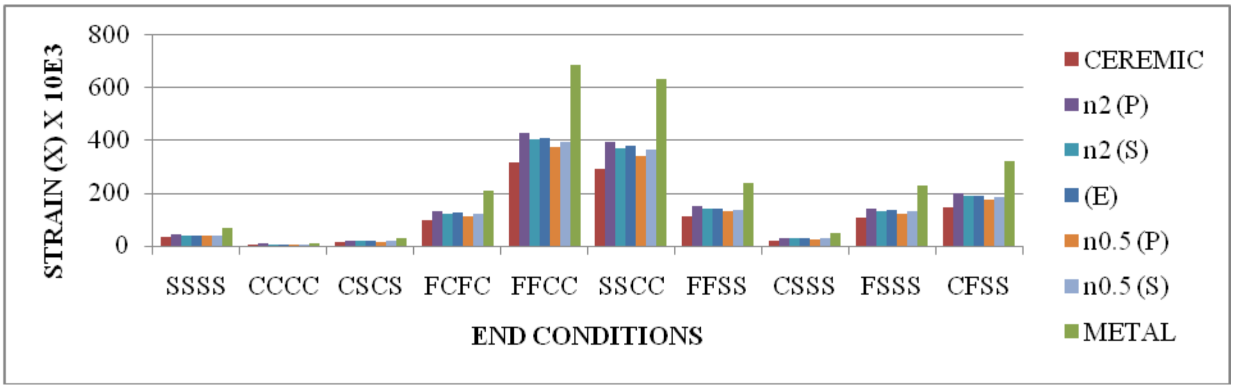

Figure 12: Effect of Boundary Conditions on Strain (ex) for FGM's, Metal and Ceramic.

Figure 12 shows the variation of strain for various types of plate which are n:0 (Ceramic), n:$\propto$ (Metal), P(Power)-FGM (n:0.5 & 2), S(Sigmoid)-FGM (n:0.5 & 2) and E (Exponential)-FGM. It is clear that the strain under the FFCC end condition in case of n2 (P) (e_x = 0.43) and that of n2 (S) is (e_x=0.4). Strain for E-FGM (e_x = 0.41) is more than that of n2 (S) and less than that of n2 (P).

3.1.5 Shear Strain (exy)

Table 9 and 10 show the values of shear strain and Figure 13 and Figure 14 show the comparative charts for various end conditions.

It is stated that

- The boundary condition (SSFF) gives maximum shear strain while boundary condition (CCCC) gives minimum value.
- The lowest shear strain (e_{xy}) is observed for pure ceramic plate whereas the largest shear strain is observed for pure metallic plate.

Table 9: Effect of End Conditions on Shear Strain (e_{xy} x1000) for P (Power)-FGM

	P-FGM						Exp.-FGM
END CONDITIONS	n=0	0.5	1	2	5	100	
SSSS	15	22	25	28	29	32	26
CCCC	0.4	0.6	0.7	0.7	0.8	0.9	1
CSCS	7.1	10	11	12	13	14	12
FCFC	5.3	7.4	8.5	9.5	9.9	10	9
FFCC	22	32	36	40	43	46	38
SSCC	21	30	34	38	40	43	36
FFSS	92	130	149	165	173	188	156
CSSS	13	18	20	23	24	26	22
FSSS	22	31	36	40	42	45	37
CFSS	14	20	24	26	27	30	25

Table 10: Effect of End Conditions on Shear Strain (e_{xy} x1000)for S (Sigmoid)-FGM

	S-FGM						
END CONDITIONS	n=0	0.5	1	2	5	100	∝
SSSS	15	24	25	27	28	28	34
CCCC	0.4	0.6	0.7	0.7	0.7	0.8	0.9
CSCS	7.1	10	11	12	12	12	15
FCFC	5.3	8.1	8.5	9.0	9.4	9.6	11
FFCC	22	35	36	39	40	41	49
SSCC	21	32	34	36	37	38	46.1
FFSS	92	141	149	154	164	167	199
CSSS	13	19	20	22	23	23	28
FSSS	22	34	36	38	39	40	48
CFSS	14	22	24	25	26	26	32

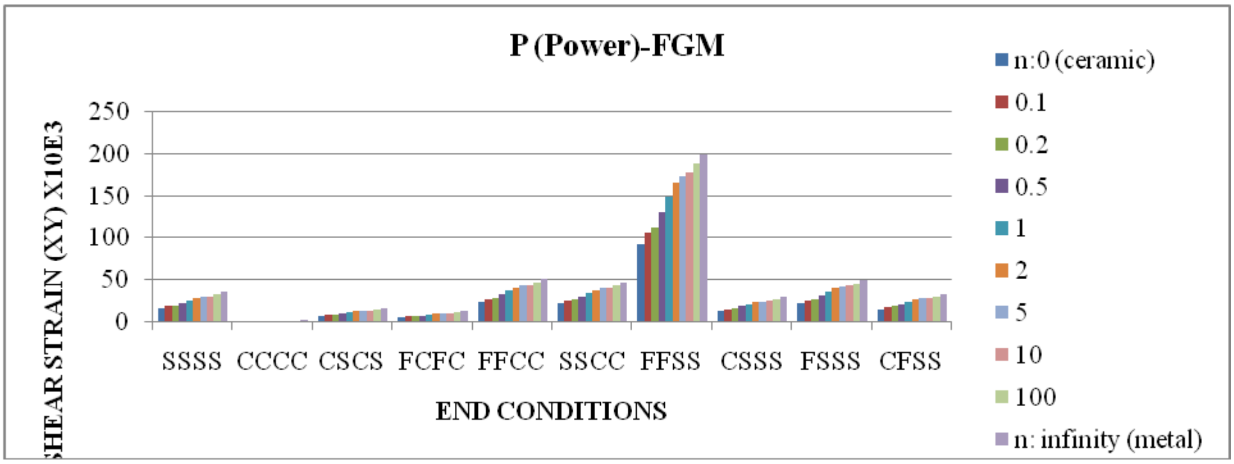

Figure 13: Effect of End Conditions on Shear Strain (e_{xy}) for P (Power)-FGM.

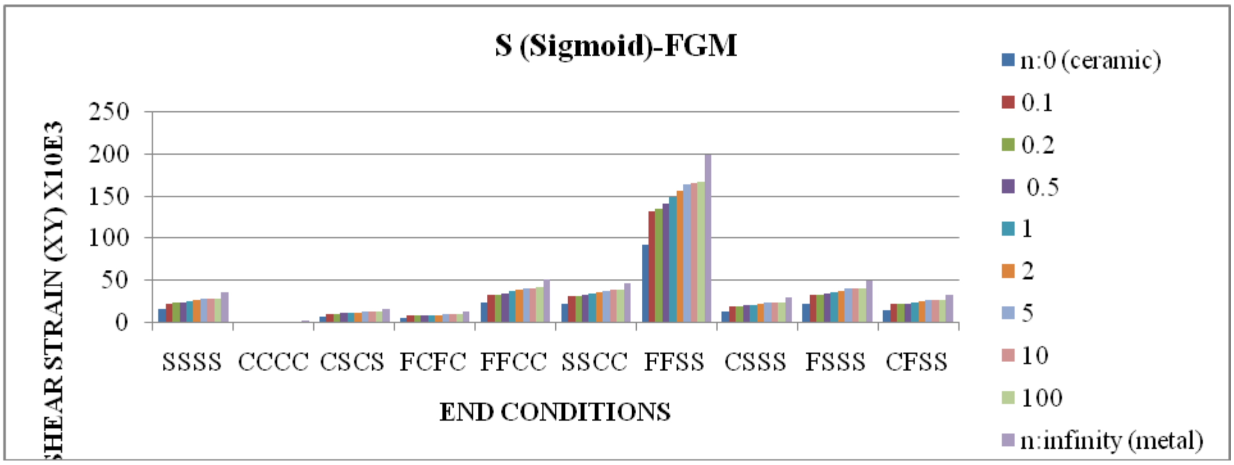

Figure 14: Effect of End Conditions on Shear Strain (e_{xy}) for S (Sigmoid)-FGM.

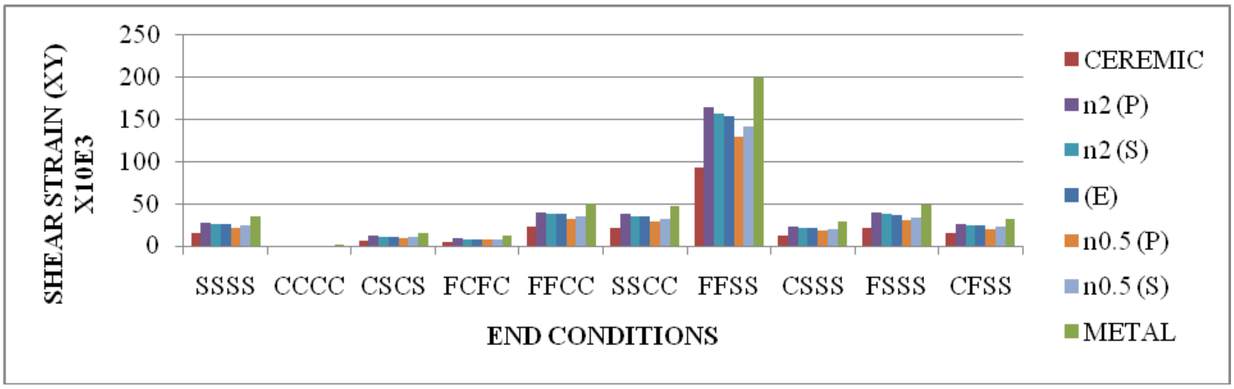

Figure 15: Effect of End Conditions on Shear Strain (exy) for FGM's, Metal and Ceramic.

Figure 15 shows the comparison of shear strain for various types of plate which are n:0 (Ceramic), n:∝ (Metal), P(Power)-FGM (n:0.5 & 2), S(Sigmoid)-FGM (n:0.5 & 2) and E (Exponential)-FGM. It is clear that the shear strain under the FFSS end condition in case of n2 (P) (e_{xy} = 0.165) and that of n2 (S) is (e_{xy} = 0.154). Shear strain for E-FGM (e_{xy} = 0.156) is more than that of n2 (S) and less than that of n2 (P).

Figure 12 shows the variation of strain for various types of plate which are n:0 (Ceramic), n:∝ (Metal), P(Power)-FGM (n:0.5 & 2), S(Sigmoid)-FGM (n:0.5 & 2) and E (Exponential)-FGM. It is clear that the strain under the FFCC end condition in case of n2 (P) (e_x = 0.43) and that of n2 (S) is (e_x=0.4). Strain for E-FGM (e_x = 0.41) is more than that of n2 (S) and less than that of n2 (P).

4. CONCLUSIONS

Central point load is applied on FGM plate and response is presented in terms of geometric parameters by the variation of material gradation and end conditions. The conclusions are:

- With increase of the 'n' non-dimensional deflection becomes more and more. It may be explained with the concept of the modulus of elasticity and stiffness which is highest for plate made of ceramic, while least for plate made of metal.
- The value of non-dimensional parameters for FG plate is lying in between metal and ceramic plate.

- FFSS end condition gives the maximum deflection and all ends fixed i.e. CCCC end condition gives minimum.
- FFCC end condition gives the maximum tensile stress while CSCS end condition gives minimum tensile stress. CCSS boundary condition gives second highest value of tensile stress amongst all the cases considered here. SSFF boundary condition gives the maximum non-dimensional shear stress ($\overline{\sigma_{xy}}$) while CCCC boundary condition gives its value to minimum among all the cases considered here.

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